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SECOND MANNED EVALUATION OF THE PROTOTYPE MK 12 SSDS, HELIUM-OX--ETC(U)
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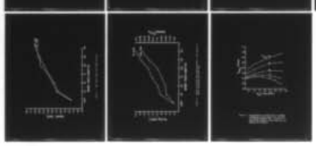

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# Navy Experimental Diving Unit

DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
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# SECOND MANNED EVALUATION OF THE PROTOTYPE MK 12 SSDS, HELIUM-OXYGEN MODE

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14 March 1978



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The Prototype MK 12 SSDS, Helium-Oxygen System, was evaluated to test the ability of the system to support a working diver. The study was performed in two parts. First, helmet $CO_2$ levels during graded exercise were measured to ensure that helmet ventilation is adequate to support a diver performing sustained heavy work, equivalent to an oxygen consumption of 3 liters per minute. Secondly, cannister effluent $CO_2$ levels

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were measured during prolonged moderate work, equivalent to a $CO_2$ production of 1.5 liters/minute, to establish cannister duration. Analysis of the data clearly shows that while helmet ventilation is adequate to support a diver performing sustained heavy work for short periods, cannister duration was inadequate to support moderate work throughout an operational dive.

ABSTRACT

The Prototype MK 12 SSDS, Helium-Oxygen configuration was evaluated to test the ability of the system to support a working diver. The study was performed in two parts. First, helmet $CO_2$ levels during graded exercise were measured to ensure that helmet ventilation is adequate to support a diver performing sustained heavy work, equivalent to an oxygen consumption of 3 liters per minute. Secondly, cannister effluent $CO_2$ levels were measured during prolonged moderate work, equivalent to a $CO_2$ production of 1.5 liters/minute, to establish cannister duration. Analysis of the data clearly shows that while helmet ventilation is adequate to support a diver performing sustained heavy work for short periods, cannister duration was inadequate to support moderate work throughout an operational dive.

# SECOND MANNED EVALUATION OF THE PROTOTYPE MK 12 SSDS, HELIUM-OXYGEN MODE

In February 1977, the Navy Experimental Diving Unit conducted a manned evaluation of the U.S. Navy Prototype Mark 12 Surface Supported Diving System (MK 12 SSDS). The results of that study were published in Navy Experimental Diving Unit Report 10-77 in September 1977 (O'Bryan). In summary, the results clearly demonstrated that the system could support temporarily a diver performing heavy work. However, the life expectancy of the carbon dioxide absorbing bed was shown to be insufficient to allow a diver to complete an operational dive at normal working depths.

The MK 12 SSDS recirculator assembly consists of a manifold, an ejector, an emergency gas bottle, associated valves and hoses, and a $CO_2$ absorbent bed contained in a 5.7 liter cannister. During normal operations, surface-supplied gas is delivered to the manifold of the MK 12 SSDS recirculator assembly. Here the gas is directed to the ejector, which is positioned in such a way that a venturi action secondary to gas flow through a .028" diameter orifice entrains gas from the $CO_2$ absorbent bed, drawing additional helmet gas into the cannister, and sends scrubbed and supply gas back into the helmet. Thus, a small ejector flow creates a system flow sufficient for adequate helmet ventilation and carbon dioxide absorption.

Recent evaluations of the MK 12 SSDS indicate that cooling of exhaled gas and subsequent rewarming of the gas within the carbon dioxide absorbent bed leads to significant drying of $CO_2$ absorbent material with deterioration in performance. Modification of the MK 12 SSDS recirculator assembly has resulted in the encorporation of two moisture retaining condensers within the body of the cannister (Figure 1). Unmanned studies now indicate that the life expectancy of this cannister, utilizing High Performance Soda-sorb (W. R. Grace Chemical Corporation), is in excess of ten hours when subjected to an average load of 1.5 liters per minute of carbon dioxide when the helmet ventilation rate is 6 ACFM. To confirm the capability of the Prototype MK 12 SSDS to support a working diver, the system was evaluated at its operational depth during the decompression phase of a 1500 FSW experimental saturation dive conducted at NEDU during November and December of 1977.

Several factors affect the ability of a diver to perform sustained work while diving in a helmeted system. The most important of these is the level of carbon dioxide ($P_{CO_2}$) inside the helmet. This value is highly dependent upon adequate ventilation of the helmet. In the MK 12 SSDS in the recirculating mode, the helmet $CO_2$ level is dependent not only upon adequate helmet ventilation, but also upon an efficient carbon dioxide absorbent bed with a long duration of action. Therefore,

the present study had two objectives:

(1) Test the adequacy of helmet ventilation in this recirculating helmet system during sustained heavy work, equivalent to an oxygen consumption of 3 liters/minute,

(2) Establish the duration of the carbon dioxide absorbent bed during prolonged moderate work, equivalent to an average $CO_2$ production of 1.5 liters/minute.

## METHODS

The simulated dive was conducted in the Ocean Simulation Facility of the Navy Experimental Diving Unit. Six experienced, U.S. Navy male divers served as subjects. Physical characteristics of the men are depicted in Table 1. All subjects performed extensive calisthenics, distance runs up to 7 km, and periodic swims in excess of 1000 meters five days per week for nine weeks prior to the study. In addition, each man performed in excess of twenty underwater work cycles, similar to the experimental protocol, during this work-up period.

Each diver wore the Prototype MK 12 SSDS. The carbon dioxide absorbent used was High Performance Sodasorb. During baseline measurements at 32 FSW, the supply gas was 80% Helium - 20% Oxygen ($P_{O_2}$ of 299 mmHg), while at depth it was 95% Helium - 5% Oxygen ($P_{O_2}$ varying from 556 mmHg at 450 FSW to 268 mmHg at 200 FSW). The mixtures were delivered to the ejector manifold via 600 feet of MK 12 umbilical hose at overbottom pressures calculated to produce a system flow of 6 ACFM, previously reported by Thalmann (1974) to prevent helmet $P_{CO_2}$ from exceeding the Navy limit of 15.2 mmHg (2% SEV) with a diver performing work equivalent to an oxygen consumption ($\dot{V}O_2$) of 3 liters per minute. The overbottom pressure used at 32 FSW was 26 psig. Those utilized at depth can be determined by referring to Figure 2.

The initial portion of the experimental protocol evaluated the life expectancy of the carbon dioxide bed. It consisted of six-minute work periods, separated by four minutes of rest, at a work rate of 50 watts on an especially modified pedal ergometer (James 1976) mounted vertically on a frame approximately ten feet underwater. This work-rest sequence was selected to approimate an average delivery of 1.5 liters of carbon dioxide per minute. The water temperature varied from 4.4 to 12.8°C. The study began at a depth of 450 FSW and was conducted during standard U.S. Navy Saturation Decompression (6 feet/hour up to 200 FSW). The only parameter recorded was a continuous analysis of the carbon dioxide fraction of the cannister effluent. This was accomplished by venting a sample of cannister effluent via an 1/8" O.D. tube at an appropriate flow rate to a mass spectrometer located outside the chamber. Exercise was designed to continue until "cannister breakthrough", defined in this study as the point at which cannister effluent $P_{CO_2}$ attained a value of 0.5% SEV (3.8 mmHg). If the first diver became fatigued prior to "cannister breakthrough", another diver was substituted, and the experiment continued. During the diver changeout the recirculator was left operating to maintain absorbent activity.

The second phase of the study evaluated the ability of the system to support a diver performing sustained heavy work for short periods. It was conducted at 300 FSW and consisted

of exercise sequences as described above with one exception: work began at 25 watts and was increased by 25 watts during each successive work period until diver exhaustion occurred. Conventional ECG leads were fastened on the divers' Chests for measurements of heart rates. Gas samples from the recirculator inlet and outlet were analyzed by a mass spectrometer as described above. Throughout the final minute of each exercise sequence continuous recordings were made of heart rate, and the carbon dioxide fraction of the gas passing into and out of the recirculator. Water temperature was maintained at 15.6°C.

RESULTS

Figure 3 portrays cannister effluent $P_{CO_2}$ versus time in minutes at a depth of 32 FSW in water at a temperature of 4°C. The mean time to breakthrough for these cannister duration studies was 332 minutes with a standard deviation of 44 minutes. Figures 4, 5, and 6 depict the same information derived from cannister studies at depths between 450 and 200 FSW at water temperatures ranging from 4 to 12.8°C. At 4°C (Figure 4) the first cannister became exhausted at 152 minutes, with only one diver required to reach breakthrough. During the second study in 4.4°C water the first diver became fatigued at a time when cannister effluent reached 0.13% SEV. During diver changeout there was turn over time of 30 minutes. Upon continuation of the study, the cannister effluent fell to 0%,

and continued at that level for another 1.25 hours. This phenomenon was felt to be due to rewarming of the cannister in a 29.4°C chamber during diver turnover. Due to the study impinging upon the nighttime hours, the study was stopped at a total time on the cannister of 5 hours 46 minutes, at which time the cannister effluent was 0.37% SEV. Since it has been repeatedly demonstrated at NEDU that the time to breakthrough once cannister effluent contains measureable $CO_2$ is quite reproducible for a given MK 12 SSDS cannister, the time to cannister breakthrough on the second cannister at 4°C was extrapolated from the data contained on the first diver, and was recorded as 230 minutes. Thus, the mean cannister duration at 4°C was 191 $\pm$ 55 minutes. In 10°C water (Figure 5) diver turnover occurred at a time when cannister effluent reached 0.49% SEV. When the second diver continued the study the effluent $CO_2$ fraction fell to 0.24% SEV, and rapidly proceeded to breakthrough. The actual breakthrough time, however, was extrapolated, as previously described, and recorded as 330 minutes. The mean time for cannister breakthrough for all cannisters studied at depth was 255 $\pm$ 81 minutes.

Figure 7 shows mean heart rates, plotted against work load at 32 and 300 FSW. The heart rate, which is directly proportional to oxygen consumption, and hence to carbon dioxide production, increased in a linear fashion with increasing work

loads. The plots obtained are similar, and the mean heart rates for the maximum work loads at 32 and 300 FSW were 156 and 158 respectively. If one assumes actual work output to be 33% greater than that indicated on the ergometer, to account for the work of moving the legs with diving dress through the water (Costill 1971), and if the heart rates are correlated with values obtained during work in air in a dry laboratory at 1 atmosphere (Astrand 1970), the oxygen consumption, and thus the carbon dioxide production, approximates 3 liters per minute.

Figure 8 shows mean helmet $P_{CO_2}$ levels for the graded exercise sequences at 32 and 300 FSW. Other than the 150 watts work cycle at 32 FSW, at no time did mean helmet $P_{CO_2}$ reach 2% SEV (15.2 mmHg). During each rest period the helmet $P_{CO_2}$ decreased to less than 0.5% SEV. At no time during graded exercise did cannister effluent contain measureable carbon dioxide.

## DISCUSSION

In the design and testing of any prospective underwater breathing apparatus it is imperative that due attention be paid to ensure that the life support characteristics of the equipment at no time limits the ability of a diver to increase ventilation in the face of increasing ventilatory requirements. To do so may lead to an increase in the

amount of carbon dioxide in the tissues and result in a number of physiological consequences that could prove hazardous or even fatal to a diver. Among these are: (1) decreased mental and physical performance; (2) potentiation of inert gas narcosis, decompression sickness, and oxygen toxicity; and (3) progressive somnolence possibly resulting in unconsciousness.

Restrictions to ventilation usually result from one of two factors. First, elevated breathing gas density increases the resistance to gas flow in the airways of the lungs and in the breathing apparatus. This can result in either an excessive work of breathing with a subsequent deterioration of useful work output, or a reduction in adequate ventilation accompanied by carbon dioxide retention. If the restriction is sufficiently severe, both a reduction in potential work output and carbon dioxide retention may occur. The second factor that may lead to inadequate "effective" ventilation is elevated carbon dioxide levels in a diver's breathing gas. In such a situation, the diffusion gradient for $CO_2$ between the blood and breathing gas is reduced, and in order to maintain normal $CO_2$ transport out of the body, there must be a corresponding increase in ventilation.

The Prototype MK 12 SSDS used in this study is a recirculating helium-oxygen system. The use of helium-oxygen rather than air obviated ventilatory restrictions due to increased gas density at the depths of this study. The use of a helmet in a recirculating mode with carbon dioxide absorption, however, can lead to increased ambient carbon dioxide with resultant carbon dioxide retention if ventilation or $CO_2$ absorption is inadequate. Since helmet $P_{CO_2}$ levels are dependent upon $CO_2$ production, absorption, and helmet ventilation, the purpose of this study was to ensure that the system could support a diver performing work equivalent to 3 liters of oxygen consumption per minute, and to establish the life expectancy of the $CO_2$ absorbent bed when subjected to prolonged moderate work, equivalent to a $CO_2$ production of 1.5 liters/minute.

Helmet Ventilation

As shown in Figure 8, mean helmet $P_{CO_2}$ during graded exercise remained below 2% SEV in all instances except for the 150 watts work load at 32 FSW where mean $P_{CO_2}$ levels reached 2.2% SEV (16.7 mmHg). Sinclair, Clark and Welch (1971) demonstrated that exercise in air with an ambient $P_{CO_2}$ of 21 mmHg resulted in small increases in arterial $P_{CO_2}$ (3.6 mmHg) at light work loads that decreased to near mean resting control levels at heavy work loads. This work was subsequently supported by Clark (1973) when he demonstrated

that progressive rises in arterial $P_{CO_2}$ with increasing work loads did not occur when ambient $P_{CO_2}$ was 20 mmHg or less (Figure 9). The $CO_2$ levels demonstrated in the present study were well below the 21 mmHg used by Sinclair, Clark, and Welch, and the 20 mmHg of Clark, and in general were below the Navy limit of 15.2 mmHg. The one instance where mean helmet $P_{CO_2}$ exceeded 2% SEV can be explained on the basis of helmet flows less than 6 ACFM. Near the surface small variations in overbottom pressure cause significant variations in the flow through the ejector nozzle. At depth, however, ejector flow varies little with the small pressure fluctuations encountered. At no time during graded exercise were measureable quantities of carbon dioxide found in the cannister effluent. Since the maximum work loads at 32 and 300 FSW approximated 3 liters/minute of oxygen consumption, it can be concluded from the above results that the helmet ventilation of the Prototype MK 12 SSDS is sufficient to support a diver performing sustained heavy work provided the carbon dioxide absorbing bed remains active.

## Cannister Duration

Figure 3, 4, 5 and 6 graphically show the results of cannister breakthrough studies conducted between 450 and 200 FSW. As discussed previously the curves obtained from the second cannister study in 4°C water, and the curve obtained

from the cannister study in 10°C water were extrapolated to the 0.5% SEV $CO_2$ level utilizing the data obtained on the first diver in those studies. When thus viewed, all curves are remarkably similar, and basically vary only at the point in time at which cannister effluent $CO_2$ begins to rise. The mean of all cannister studies at depth was $255 \pm 55$ minutes.

It is apparent from the above results that the capability of the Prototype MK 12 SSDS to support a diver performing prolonged moderate work during an operational dive, which could easily last more than six hours, is inadequate. The results do, however, lend insight into a basic problem of carbon dioxide absorption in cold water.

Two findings of interest that emerged from the cannister breakthrough studies were the increased duration of action of the absorbent bed in warmer water, and a return to higher efficiency during diver turn-over in two of the cannister studies. The first finding came as no surprise, and is well supported in the literature. The second finding, however, was a surprise during data collection, but upon reflection made sense. In each cannister study, absorbent activity began in an 29.4°C chamber for several minutes prior to being immersed in cold water. If degradation of cannister function occurred as a result of absorbent bed cooling rather than by chemical exhaustion, one would expect that a return to an 29.4°C chamber and continued scrubbing activity would restore bed

activity. This is what was observed, and the conclusion is that the degradation of cannister function is not only secondary to chemical exhaustion, but also due in part to slow cooling of the absorbent bed.

## SUMMARY

The Prototype MK 12 SSDS helium-oxygen recirculating mode was evaluated at its operational depth. The results clearly demonstrate that while the system can support a diver performing heavy work, it cannot support a diver in cold water for sufficient time to complete an operational dive at normal working depths. Since the results support the conclusion that the degradation of cannister bed efficiency is due in part to a slow cooling of the absorbent bed, improvements in the cannister should include improved thermal protection of the cannister, and possible gas heating.

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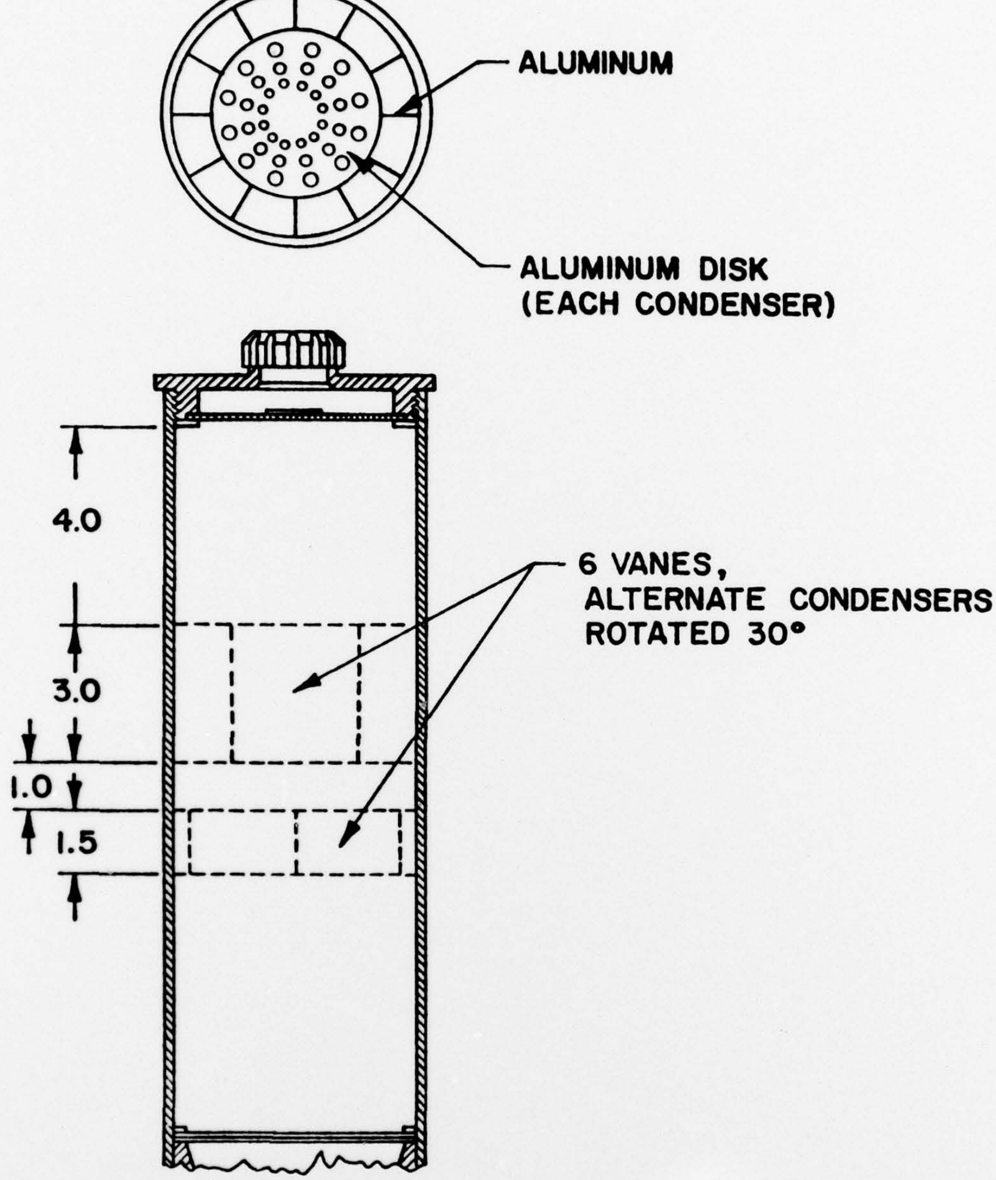
TABLE I

Physical Characteristics of Divers

| Diver | Age | Height (cm) | Weight (Kg) |
|---|---|---|---|
| 1 | 31 | 175.3 | 87.2 |
| 2 | 36 | 172.7 | 83.1 |
| 3 | 32 | 180.3 | 91.6 |
| 5 | 25 | 177.8 | 83.5 |
| 6 | 26 | 170.2 | 73.5 |




MK 12 SSDS CURRENT CANISTER CONFIGURATION
FIGURE 1

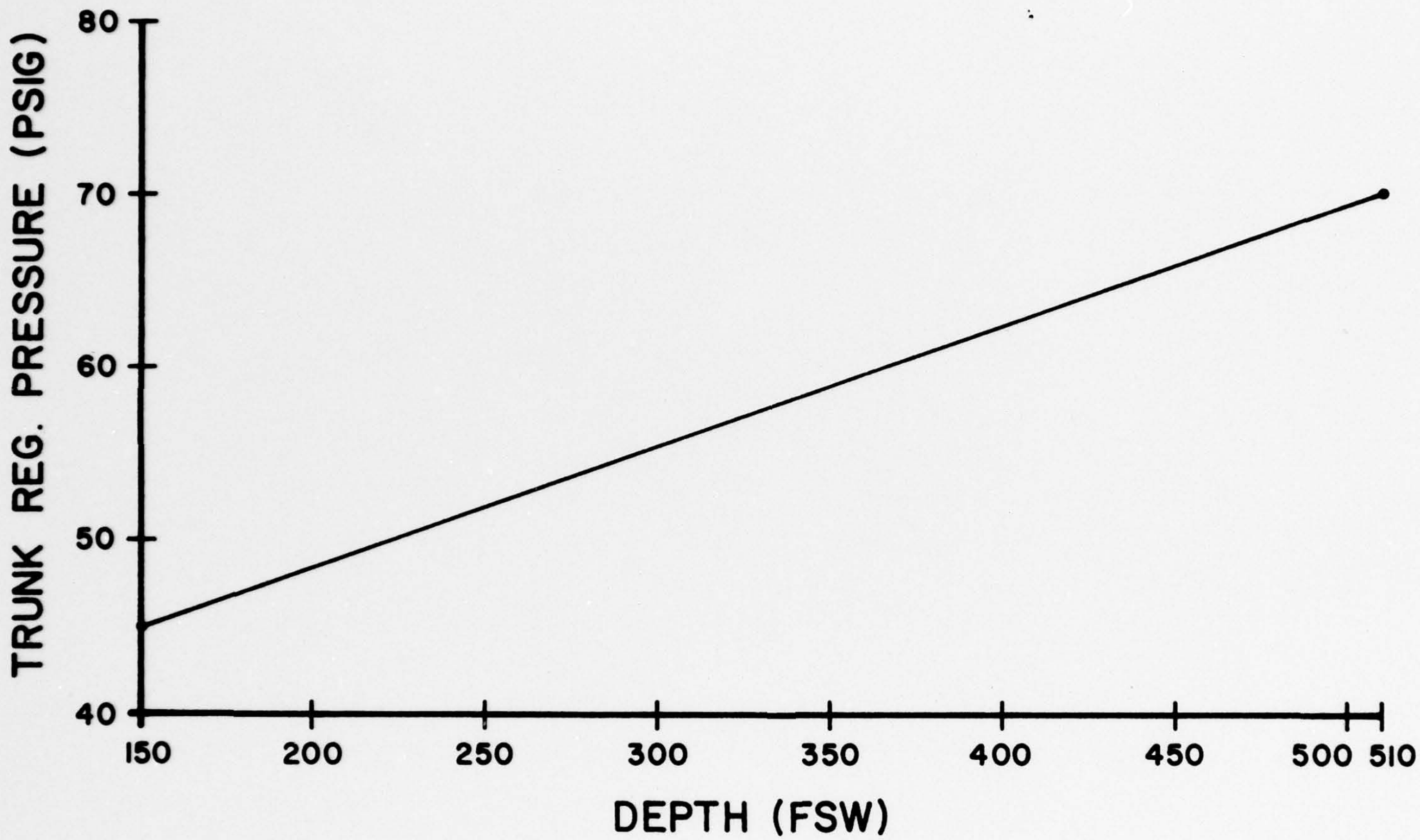



**Figure 2.** Overbottom pressures to MK 12 SSDS that provide system flow of 6 ACFM versus depth using 95% Helium - 5% oxygen

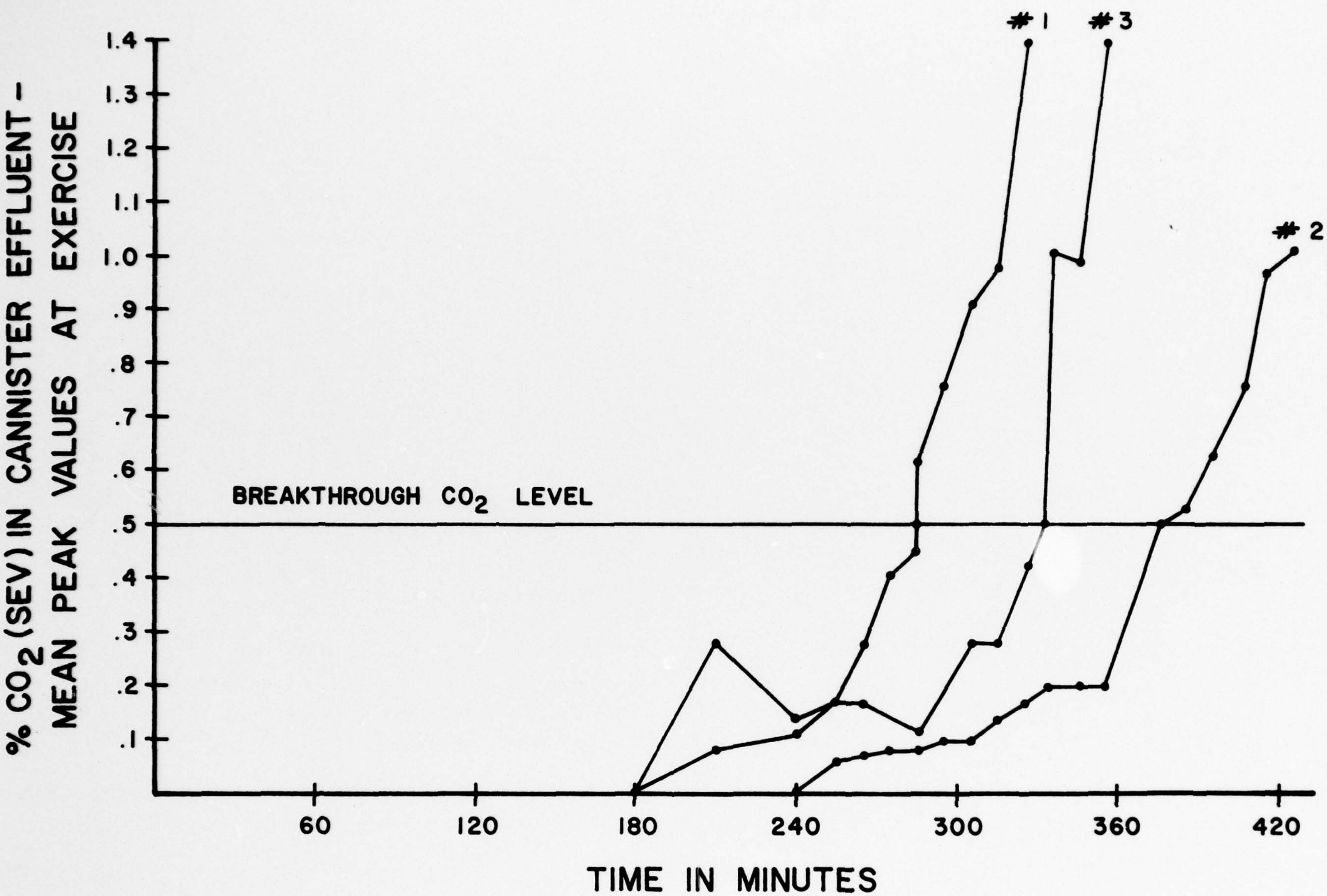



Figure 3. Canister breakthrough, 32 FSW, water temperature 4.4°C

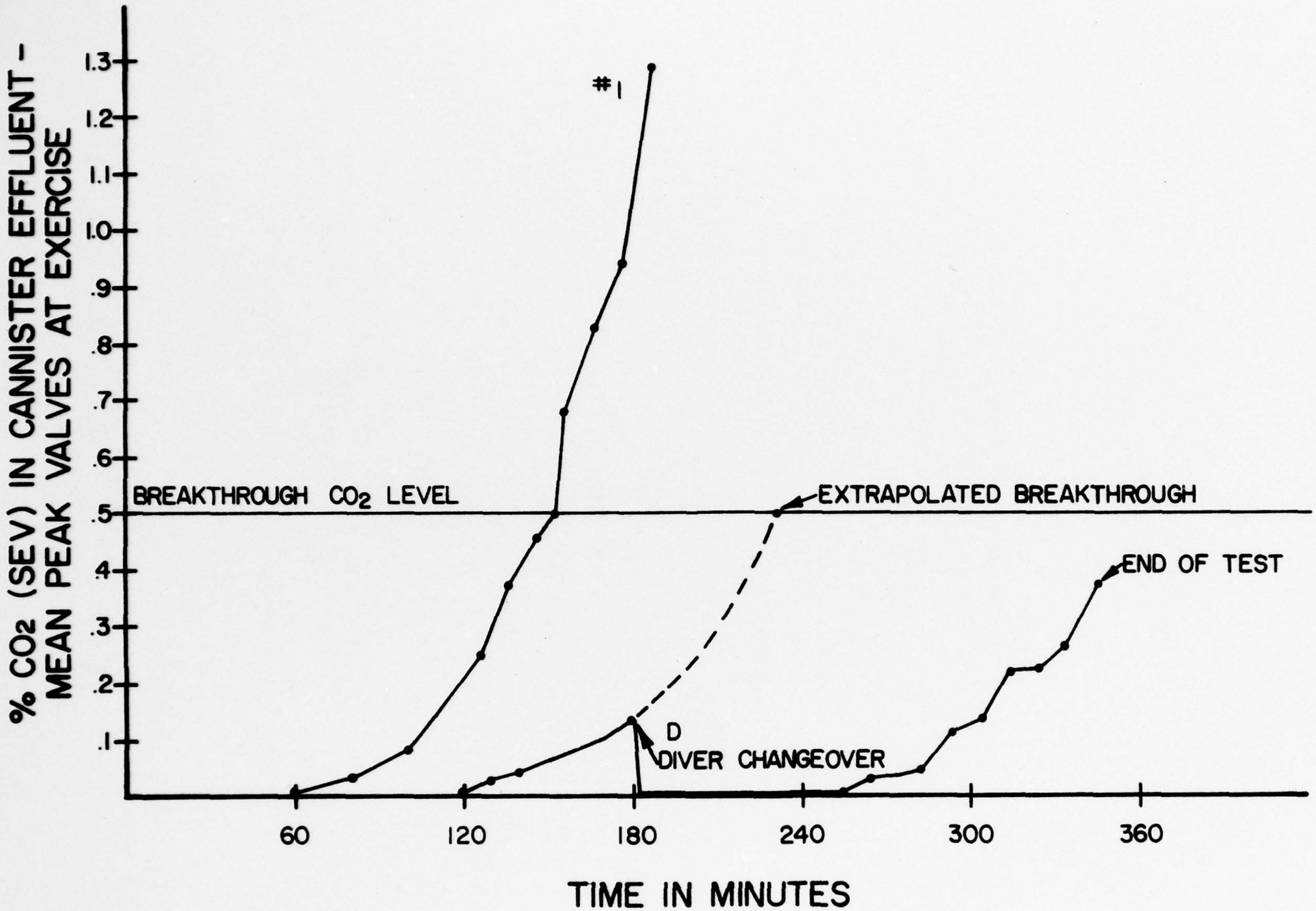



Figure 4. MK 12 canister breakthrough, 450-400 FSW, water temperature 4.4°C

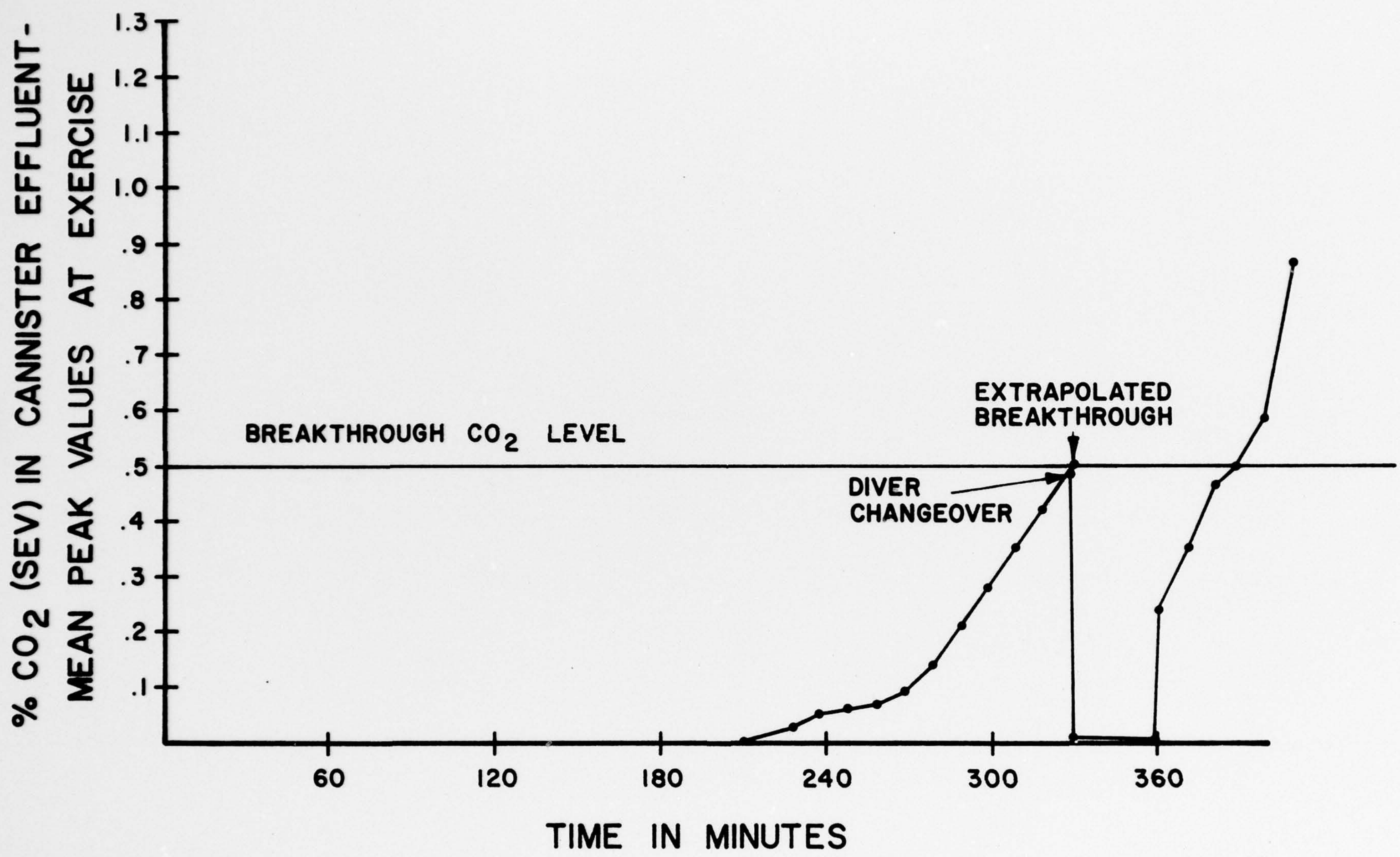



Figure 5. Canister breakthrough, 380-340 FSW, water temperature 10°C

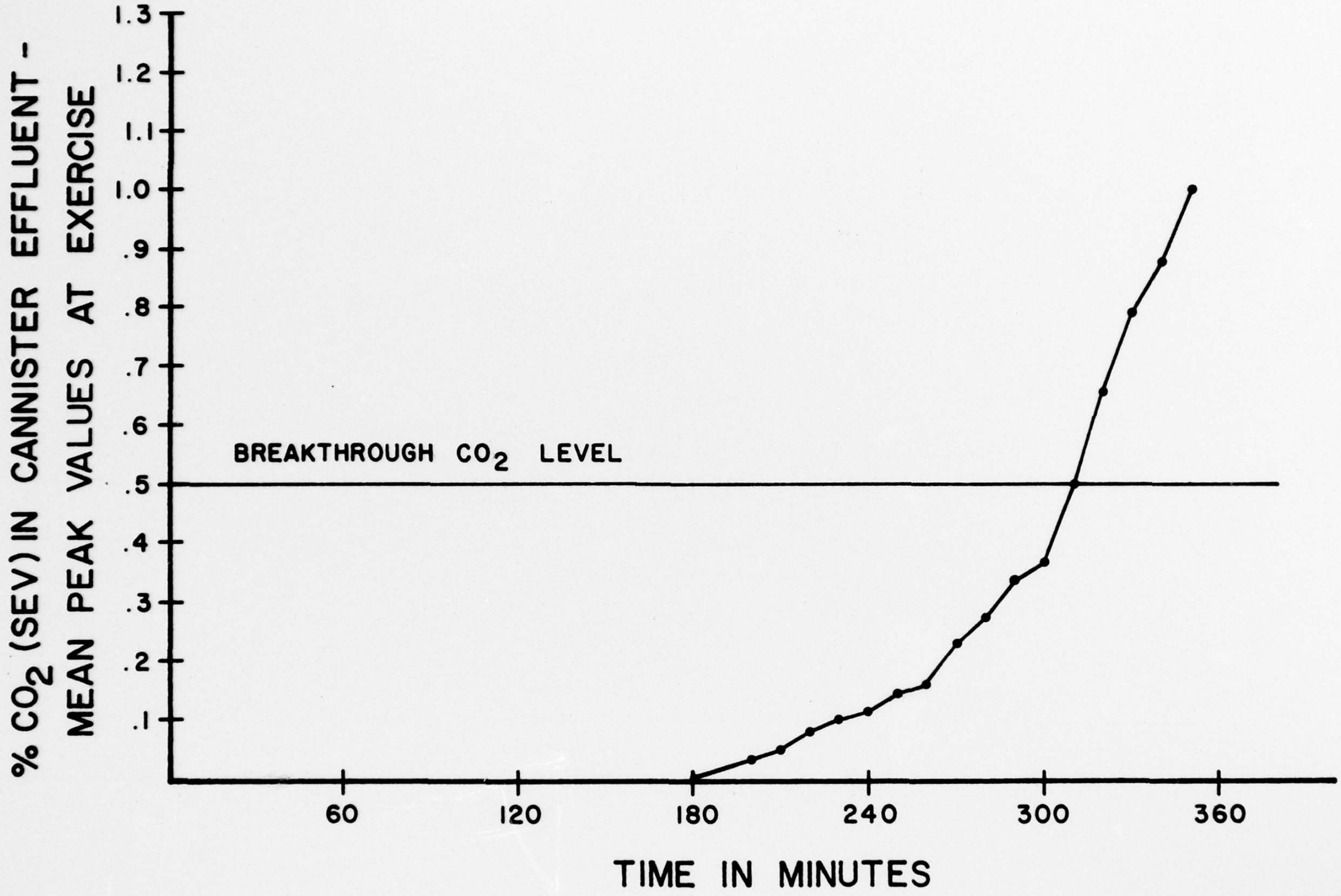



Figure 6. Canister breakthrough, 300-265 FSW, temperature 12.8°C

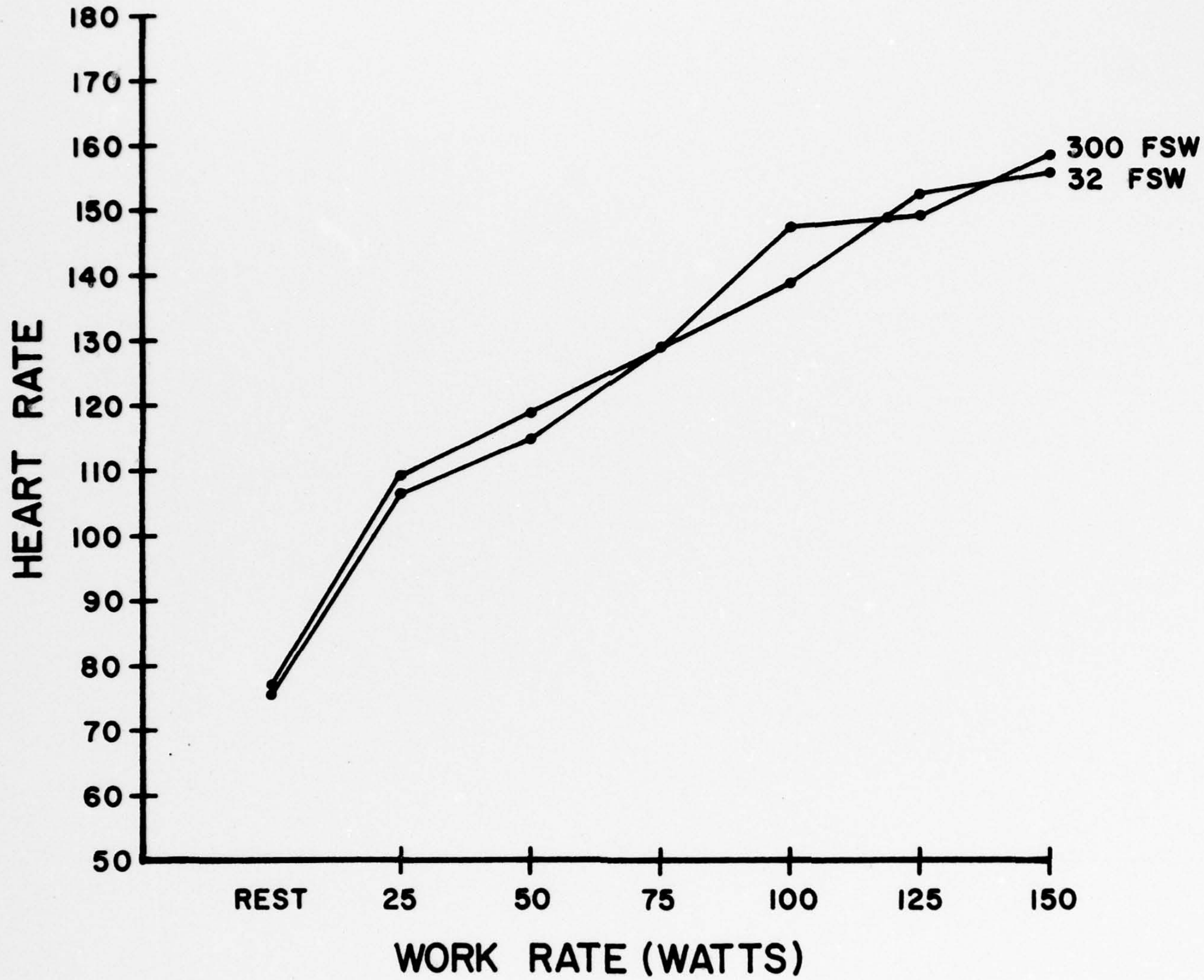



Figure 7. Mean heart rates with graded exercise

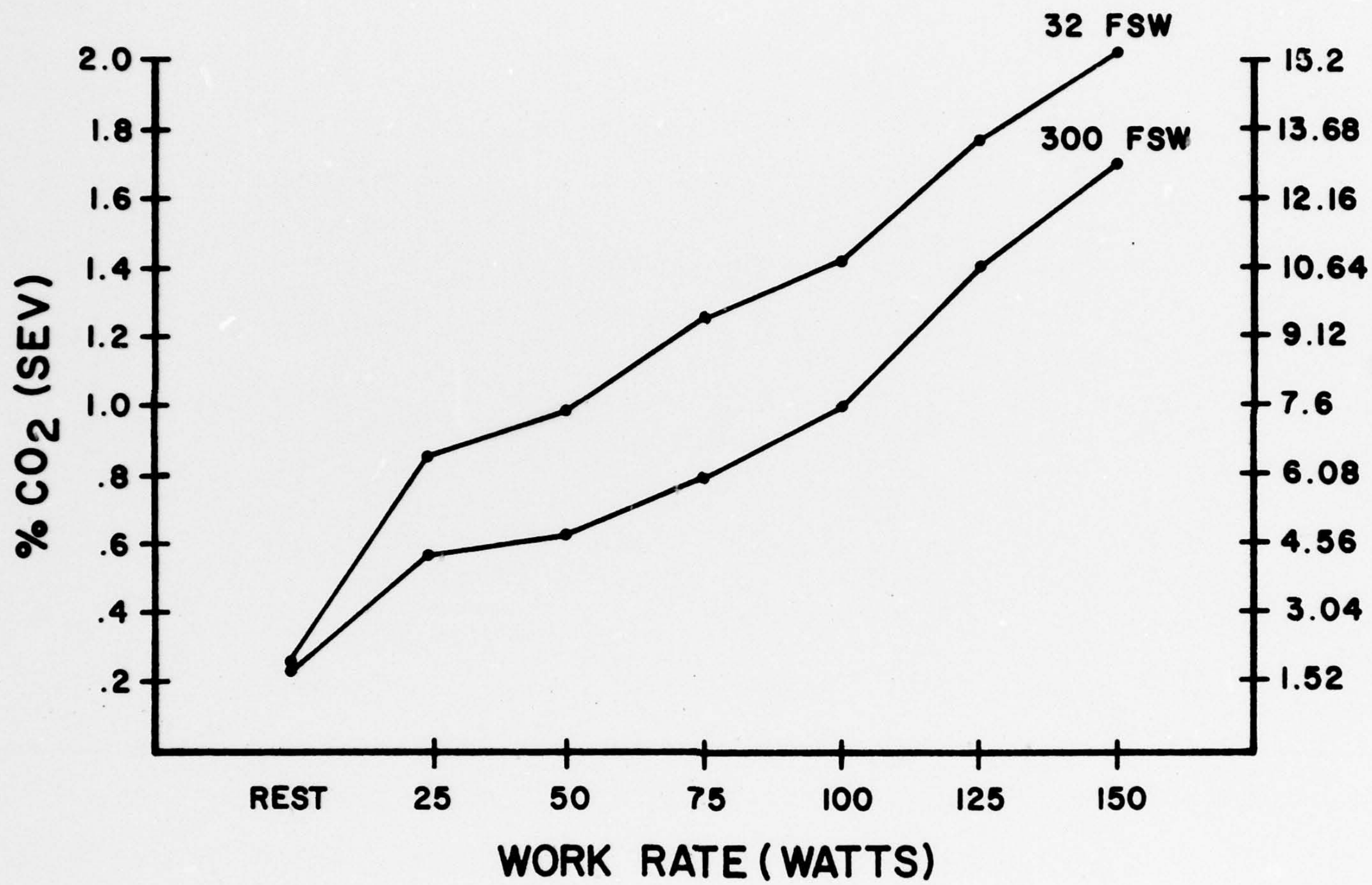



Figure 8. Helmet $CO_2$ levels with graded exercise - mean values for divers completing each work rate

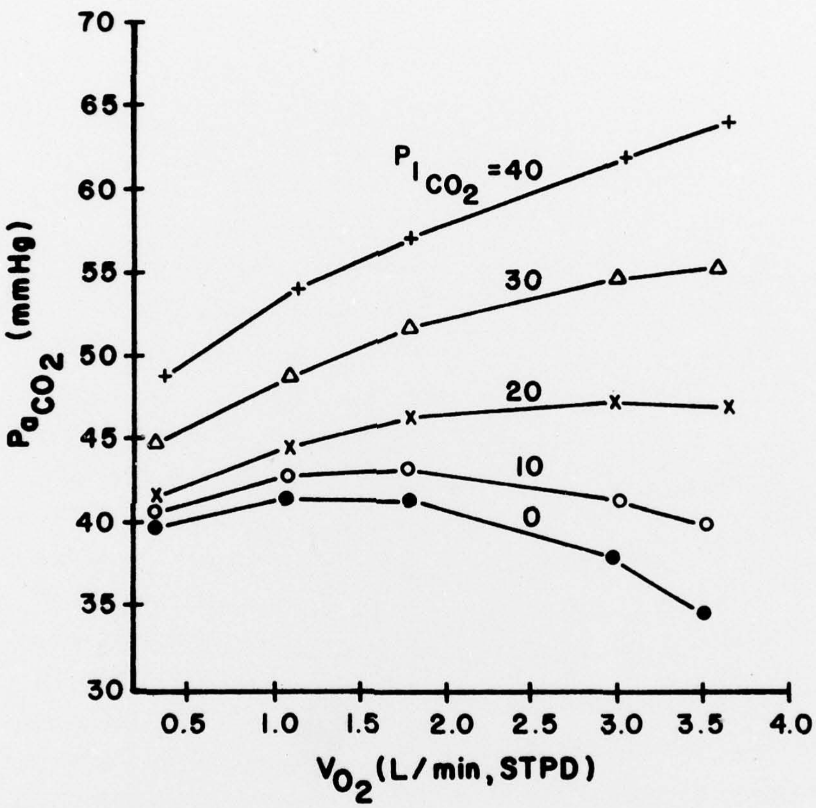



Figure 9. Relationship of arterial $P_{CO_2}$ to oxygen consumption during exposure to exercise and elevated ambient $CO_2$. Levels of inspired $P_{CO_2}$ (mmHg) for each curve are indicated on the graph.